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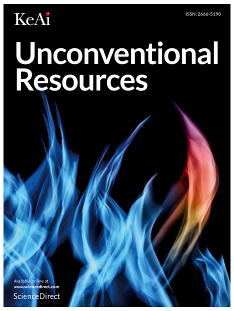

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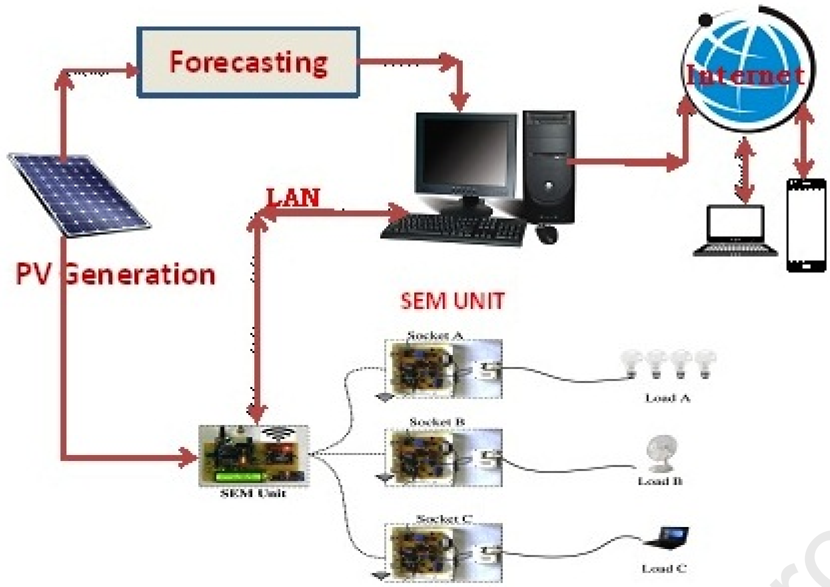
Forecasting
Internet
LAN
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Socket A
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Socket C
Load A
Load B
Load C
SEM Unit

A Comprehensive Review of Smart Energy Management Systems for Photovoltaic Power Generation Utilizing the Internet of Things

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Abstract: Renewable energy represents the most reliable and widely recognized solution for meeting the escalating global energy demands. The optimization of solar energy generation necessitates a strong focus on predictive maintenance and advanced deployment methodologies. To enhance solar power utilization, Internet of Things enabled solar monitoring systems have been proposed for real-time data acquisition and analytics, facilitating performance forecasting and ensuring consistent power output. A critical challenge in demand-side energy management lies in optimizing the integration of renewable resources while maintaining cost efficiency and minimizing energy losses. Therefore, strategic planning for the integration of renewable energy sources is imperative. Intelligent energy management systems play a pivotal role in optimizing energy distribution, particularly in scenarios with high grid dependency. Cloud computing infrastructures address the complexities and scalability challenges posed by expanding smart grids, enabling real-time data processing and adaptive energy control mechanisms. This study explores the practical implementation of energy management system in industrial settings and research domains, both of which serve as key stakeholders in advancing smart energy solutions. A comprehensive review of internet of things applications in photovoltaic power generation highlights key research objectives and technological developments in the field. The evolving landscape of internet of things driven innovations presents numerous research opportunities, including the formulation of performance evaluation metrics and the development of novel optimization techniques. Additionally, the growing emphasis on energy management within intelligent architectural frameworks underscores the necessity for deeper investigations into adaptive control strategies and system interoperability. This ongoing research is essential for driving advancements in internet of things enabled energy solutions and enhancing the efficiency of smart grid ecosystems.

Keywords: Renewable Energy, Cloud computing, Solar Energy, Forecasting, Internet of Things.

1. Introduction

The integration of the Internet of Things (IoT) has significantly revolutionized modern energy management systems, particularly in photovoltaic (PV) power generation. This study explores IoT-driven intelligent energy management systems designed to monitor, control, and optimize PV power utilization. By leveraging advanced sensor networks, data analytics, and real-time connectivity, IoT-based solutions transcend traditional energy management paradigms, offering enhanced efficiency and adaptability [1]. PV power generation plays a crucial role in addressing the growing demand for renewable and sustainable energy. However, maximizing its efficiency necessitates the deployment of intelligent systems capable of dynamically adapting to environmental variations, optimizing power distribution, and ensuring seamless integration with existing grid infrastructures [2]. This review investigates the core components of IoT-based smart energy management systems, including microcontroller selection, sensor deployment, circuit design, and network connectivity, to provide a comprehensive analysis of the technological framework [3]. Additionally, the role of cloud computing, data analytics, and IoT gateways in improving system performance, scalability, and real-time decision-making is explored.

The study aims to contribute to ongoing discussions on sustainable energy solutions by examining recent developments, existing challenges, and future applications of IoT-driven PV energy management. Furthermore, it evaluates the impact of intelligent demand-side management systems in optimizing distributed energy resources while ensuring cost-effective and resilient energy infrastructure [4, 5]. A key focus is the implementation of rooftop PV systems in urban areas, including both standalone and hybrid grid-connected models [6, 7]. Addressing challenges such as intermittent energy supply and grid stability particularly in developing regions requires hybrid energy systems that balance grid interconnectivity and self-sufficient power generation [8]. Advanced predictive models are essential for optimizing PV output under dynamic weather conditions, enhancing overall energy reliability and efficiency [9].

2. The Need for IoT in Energy Management

In the mid-1980s, data communication was primarily constrained to voice and text-based transmissions over telephone networks. With the evolution of Voice over Internet Protocol (VoIP), communication capabilities expanded significantly, leading to the development of what is now known as IoT [10–12]. IoT integrates physical devices with digital networks, enabling remote monitoring, automation, and intelligent control of interconnected systems. The first documented IoT application the Trojan Room coffee maker emerged in the early 1990s, marking the beginning of a rapidly expanding technological domain [13, 14].

The evolution of IoT can be categorized into four distinct phases:

Pre-Internet Stage: Data exchange was limited to traditional landline telephony and SMS, with early mobile devices enhancing basic communication capabilities [15].

Internet Content Phase: This phase introduced large-scale data transmission via email and web-based applications, improving information exchange [16–18].

Internet Continuous Services: The proliferation of e-commerce, digital automation, and cloud-based productivity tools characterized this stage, significantly expanding the scope of online services.

Internet of Everything (IoE): The current phase, which encompasses IoT, enables real-time connectivity between users and devices through platforms like YouTube, Facebook, and Skype. It emphasizes automation, minimal human intervention, and intelligent decision-making [19].

The emergence of IoT-driven smart grids has transformed energy distribution and demand-side management. These systems incorporate hybrid architectures integrating demand response mechanisms, distributed energy generation, power stations, microgrids, household appliances, sensor networks, and advanced communication protocols [20–22]. Smart meters deployed at consumer premises facilitate bi-directional data exchange, enabling real-time monitoring of energy consumption patterns and seamless integration with information systems. This study further explores the integration of cloud computing within smart grid infrastructures to enhance energy management efficiency. Reliable communication and data exchange systems play a vital role in mitigating power supply fluctuations and optimizing distributed generation resources [23, 24]. The analysis focuses on proactive cloud-computing techniques for IoT-enabled smart grids, emphasizing key aspects such as:

Cloud computing plays a crucial role in enhancing energy distribution and demand response by enabling high-speed computational models for smart energy supervision and real-time decision-making. These innovations demonstrate the integration of IoT, cloud computing, and smart grid technologies, driving the development of next-generation intelligent energy management solutions.

Table 1: Papers based on the search review of selected string

<table>
<tr><th>Serial number</th><th>Website</th><th>E-content</th><th>Keywords</th><th>Papers reviewed</th></tr>
<tr><td>1</td><td>www.acm.org</td><td rowspan="9">A wide range of publications are available, such as databases, magazines, articles, reports, proceedings, conferences, journals, and transactions</td><td rowspan="9">Internet of Things (IoT)applications, communication methods, difficulties and problems</td><td>83</td></tr>
<tr><td>2</td><td>www.ieeexplore.org</td><td>276</td></tr>
<tr><td>3</td><td>www.sciencedirect.com</td><td>119</td></tr>
<tr><td>4</td><td>www.scholargoogle.com</td><td>129</td></tr>
<tr><td>5</td><td>www.onlinelibrarywiley.com</td><td>84</td></tr>
<tr><td>6</td><td>www.springerlink.com</td><td>91</td></tr>
<tr><td>7</td><td>www.knowledge.com</td><td>142</td></tr>
<tr><td>8</td><td>www.elsevier.com</td><td>66</td></tr>
<tr><td>9</td><td>No of papers reviewed</td><td>991</td></tr>
</table>

The inclusion of a structured table is a critical element in this review paper, serving multiple essential functions that enhance the quality, transparency, and comprehensiveness of the research. Firstly, the table systematically organizes and presents an overview of the academic sources utilized in the literature review, highlighting key repositories such as ACM, IEEE Explore, and Science Direct. This ensures extensive coverage of the research domain and provides a valuable reference for researchers seeking relevant studies. By cataloguing keywords associated with each source, the table delineates the specific thematic focus areas of the reviewed literature, including IoT applications, communication protocols, and energy management methodologies. This structured approach facilitates an in-depth understanding of the research landscape. Moreover, by quantifying the number of papers reviewed from each repository, the table demonstrates the depth and scope of the literature review, reinforcing the study's credibility and thoroughness. Additionally, detailing the types of electronic content available from each database informs readers about the accessibility of scholarly materials, offering insights into the availability of conference proceedings, journal articles, and technical reports. The structured format of the table enhances clarity, enabling easy comparison and evaluation of sources while fostering transparency in the review process by explicitly documenting the basis for research conclusions. Beyond its immediate utility in the review, the table also provides a foundational reference for future research. It identifies repositories rich in domain-specific studies and highlights research gaps, thereby guiding subsequent investigations in IoT-driven energy management. Ultimately, the table enhances the organization and accessibility of the review, ensuring a systematic and well-structured presentation of information that strengthens the study's overall impact.

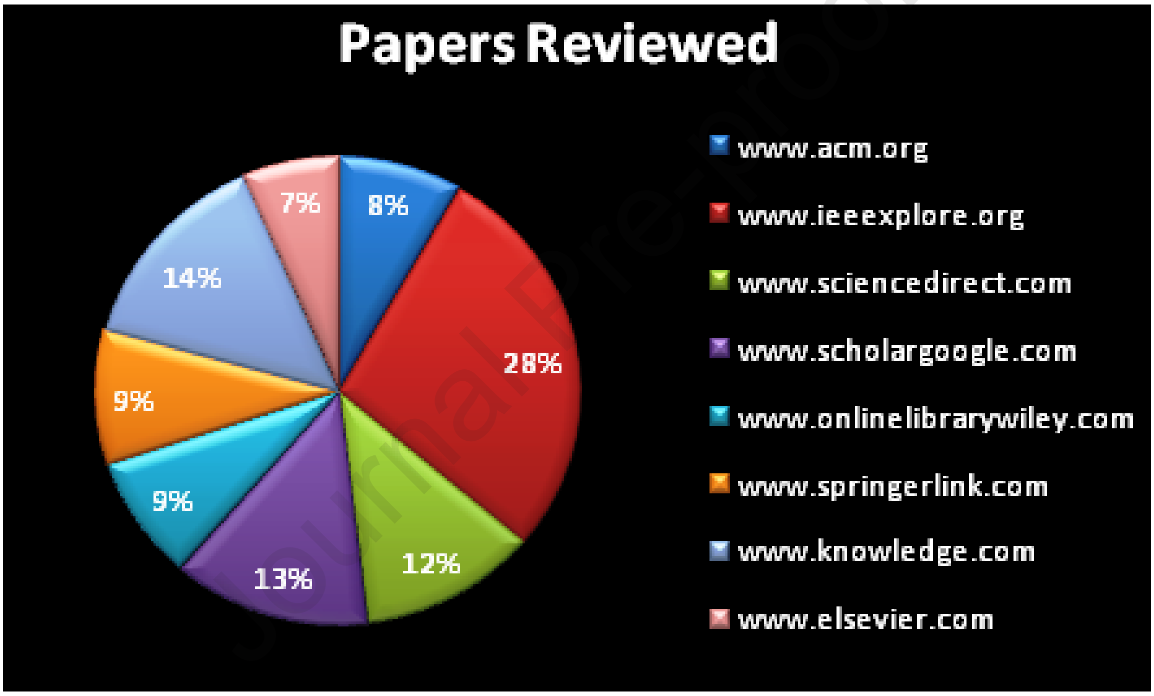


Fig.1. Pie chart illustrating publications from the literature reviews

This research conducts a comprehensive assessment of methodologies employed in prior studies, with a particular emphasis on IoT-integrated energy management techniques for PV power generation. Table 1 presents an analytical synthesis of these methodologies, highlighting the integration of IoT technology in solar energy systems. The primary objective of this review is to examine the diversity of intelligent energy management strategies applied to PV power generation, acknowledging that system-specific configurations significantly influence their effectiveness.

Practical Approaches for IoT-Based Solar Power Monitoring System

Real-Time Data Acquisition

An IoT-based solar power monitoring system begins with real-time data acquisition using smart sensors. These sensors measure key parameters such as solar panel voltage, current, temperature, and energy output [25]. Additionally, smart meters track power consumption and grid interaction, providing essential data for system optimization. Wireless communication technologies like Wi-Fi, LoRa, or GSM ensure seamless data transmission to cloud-based platforms, enabling continuous monitoring without manual intervention.

Cloud-Based Monitoring and Analysis

Cloud computing plays a crucial role in processing and analyzing the collected data. By utilizing platforms such as AWS, Azure, or Firebase, solar power systems can store, visualize, and analyze performance metrics in real time. Advanced AI (artificial intelligence) and machine learning algorithms help identify usage patterns, predict energy production, and detect anomalies. This cloud-based approach allows users to remotely monitor solar power generation through mobile and web dashboards, ensuring accessibility and efficiency.

Automated Control and Optimization

To maximize efficiency, automated control mechanisms are implemented within the system. Smart controllers regulate power flow, dynamically balancing load distribution and optimizing battery charging and discharging processes [26]. Automated switching mechanisms ensure efficient energy usage based on demand, while remote troubleshooting capabilities enable quick response to any system malfunctions. These features reduce the need for manual intervention, making solar power systems more reliable and self-sustaining.

Predictive Maintenance and Fault Detection

One of the most significant benefits of IoT in solar power monitoring is predictive maintenance. AI-powered analytics detect irregularities in system performance, allowing for early identification of potential failures. Predictive alerts notify users or maintenance teams of issues before they cause major disruptions [27]. Additionally, self-healing algorithms can automatically adjust system parameters to optimize performance and prolong the lifespan of solar panels and battery storage units.

Grid Integration and Demand Response

An effective solar power monitoring system integrates with the electrical grid to enhance energy distribution and demand response. IoT-enabled bidirectional communication facilitates net metering, allowing excess solar energy to be fed back into the grid. Energy distribution is optimized based on demand, ensuring efficient use of generated power. Furthermore, adaptive energy management strategies enhance grid resilience, helping maintain stability and reliability even during peak demand periods [28]. By incorporating IoT, cloud computing, and automation, solar power monitoring systems become more intelligent and efficient. These practical approaches ensure maximum energy utilization, reduce operational costs, and contribute to a sustainable and reliable renewable energy ecosystem.

Recent Developments in IoT-based Smart Energy Management Systems for Photovoltaic Power Generation

The integration of IoT technologies in smart energy management systems (SEMS) for PV power generation has transformed how solar energy is monitored, optimized, and distributed. Recent advancements focus on improving efficiency, real-time decision-making, automation, and smart grid interaction. Key developments include the use of AI, block chain, advanced storage solutions, and high-speed communication networks like 5G [29]. These innovations contribute to enhanced energy utilization, cost reduction, and increased sustainability.

AI and Machine Learning for Smart Energy Management

AI and machine learning are increasingly being used to optimize PV power generation. AI-driven forecasting models predict solar energy production based on weather conditions, past data, and real-time sensor inputs. Machine learning algorithms also play a crucial role in load balancing, ensuring optimal energy distribution between solar panels, batteries, and the grid. Additionally, AI-powered fault detection systems help identify potential failures in PV panels, inverters, or storage units before they occur, reducing downtime and maintenance costs [30].

Edge and Fog Computing for Real-Time Data Processing

Traditional cloud-based IoT solutions can introduce latency issues, especially in remote solar farms. To address this, edge computing processes data closer to the source on smart meters and IoT-enabled sensors—reducing dependence on centralized servers. Fog computing, which operates between edge and cloud computing, further improves real-time data analysis and decision-making. These technologies minimize energy consumption associated with data transmission, enhance security, and improve the reliability of PV systems.

Block chain for Decentralized Energy Trading

Block chain technology is revolutionizing how surplus solar energy is shared and traded. Peer-to-peer (P2P) energy trading platforms built on block chain allow PV system owners to sell excess electricity directly to consumers, reducing dependence on utility companies. Smart contracts automate transactions, ensuring secure and transparent exchanges. Additionally, decentralized energy management enables better distribution of renewable energy resources, making grids more resilient and efficient.

Advanced Energy Storage Integration

Energy storage plays a vital role in ensuring the continuous availability of solar power. IoT-based Smart Battery Management Systems (SBMS) optimize battery charging and discharging cycles based on demand and supply predictions. The integration of Vehicle-to-Grid (V2G) technology enables electric vehicles (EVs) to act as temporary energy storage units, supplying power back to the grid when needed. Furthermore, hybrid storage solutions that combine lithium-ion batteries, super capacitors, and alternative storage technologies enhance energy reliability and efficiency.

Digital Twin Technology for PV System Optimization

A digital twin is a virtual representation of a real-world PV system that simulates performance, detects faults, and optimizes efficiency. By analyzing real-time and historical data, digital twins help operators predict equipment failures and make informed decisions regarding system improvements. This technology enables enhanced predictive maintenance and contributes to better PV system design based on environmental conditions and energy consumption patterns.

5G and LPWAN for IoT Connectivity

Efficient communication networks are essential for IoT-based energy management systems. 5G technology enables faster and more reliable data transmission between PV systems, energy storage units, and grid operators, allowing real-time monitoring and control. Meanwhile, Low-Power Wide-Area Networks (LPWAN), such as LoRaWAN and NB-IoT, provide connectivity for remote solar installations with minimal energy consumption. These advancements ensure continuous data exchange and improve system responsiveness.

Smart Grid and Automated Demand Response

IoT-based PV energy systems are increasingly integrated with smart grids to enhance energy distribution and stability. Dynamic load management systems adjust electricity consumption based on solar power availability, reducing peak demand and lowering costs. Automated Demand Response (ADR) technology enables smart home devices and industrial equipment to automatically modify their energy usage based on real-time solar generation data. This reduces strain on the grid while maximizing the use of renewable energy.

Challenges and Solutions in IoT-Based Smart Energy Management Systems for Photovoltaic Power Generation

While IoT-based smart energy management systems (SEMS) have significantly improved the efficiency of PV power generation, several challenges limit their widespread adoption. These challenges include cyber security risks, high infrastructure costs, data management complexities, interoperability issues, and reliance on stable internet connectivity. Addressing these issues is essential to ensure a secure, scalable, and efficient smart solar energy ecosystem.

Cyber security and Data Privacy Concerns

As IoT devices continuously transmit and process data in real-time, they become vulnerable to cyber threats such as hacking, data breaches, and unauthorized system access. A compromised IoT network can lead to energy theft, system malfunctions, or even large-scale blackouts. Ensuring data security in IoT-enabled PV systems is crucial for maintaining operational reliability. To mitigate these risks, end-to-end encryption, multi-factor authentication, and AI-driven anomaly detection can be implemented. Additionally, blockchain-based security solutions can ensure transparent and tamper-proof energy transactions, enhancing trust in decentralized energy trading.

High Initial Costs and Infrastructure Challenges

Deploying an IoT-enabled energy management system requires investments in smart meters, cloud storage, communication networks, and edge computing infrastructure. For small-scale solar PV users, these costs can be a barrier to adoption. To make smart energy management systems more accessible, governments and energy organizations should offer financial incentives, such as subsidies and tax benefits. Additionally, modular IoT solutions allow for a phased implementation, enabling users to scale their systems gradually as per their budget. Open-source IoT platforms can also help reduce licensing costs and encourage widespread adoption.

Data Overload and Processing Complexity

The vast amount of real-time data generated by IoT-enabled PV systems poses challenges in storage, processing, and analysis. Relying solely on cloud-based data management can lead to latency issues, increased operational costs, and potential bottlenecks in decision-making. A more effective approach involves edge and fog computing, which process data closer to the source, reducing cloud dependency. AI-based data filtering algorithms can also help prioritize critical information, ensuring that only relevant insights are processed for decision-making. Furthermore, decentralized databases and block chain technology can enhance secure and efficient data management.

Interoperability and Standardization Issues

One of the major obstacles in IoT-based smart energy management is the lack of universal standards across different manufacturers. Various IoT devices and communication protocols may not always be compatible, making it difficult to integrate new components into existing PV systems. To address this, the adoption of standardized communication protocols such as MQTT, OPC UA, and IEEE 2030.5 can enhance device interoperability. Open-source frameworks and IoT gateways that translate different protocols into a common language can also facilitate seamless integration across multiple vendors, ensuring scalability and long-term sustainability.

Dependence on Reliable Internet Connectivity

Many IoT-based smart energy systems require a stable internet connection for real-time monitoring, remote control, and data synchronization. In remote or developing regions, limited network infrastructure can affect system performance, leading to inefficiencies. To overcome this, Low-Power Wide-Area Networks (LPWAN) such as LoRaWAN and NB-IoT enable long-range communication with minimal energy consumption. Additionally, offline-capable edge devices can store and process data locally, ensuring continued operation even in the absence of internet connectivity. Hybrid connectivity solutions that combine Wi-Fi, 4G/5G, and satellite networks can further enhance the resilience of IoT-based solar energy systems.

Scalability and System Complexity

As IoT networks grow, managing an increasing number of connected devices, energy sources, and storage units becomes complex. Without proper scalability planning, system performance may degrade, leading to inefficiencies. Cloud-based IoT platforms with flexible scalability can help accommodate growing energy demands. AI-driven automated energy management systems can optimize performance, adjusting in real-time as new devices are integrated. Additionally, self-healing networks that detect and resolve performance bottlenecks automatically can improve system reliability and efficiency.

To determine the optimal energy management strategies, this study critically evaluates various methodologies implemented across different IoT-enabled PV systems, as illustrated in Figure 1. Section 2 provides an in-depth discussion of selected research articles detailing IoT-based energy management frameworks. Section 4 analyzes energy management strategies within smart grids, with a particular focus on PV-based power distribution networks. Section 5 reviews literature advocating for IoT-driven control mechanisms that regulate energy flow and enhance efficiency in solar power systems. The overarching goal is to assess the adaptability and operational effectiveness of these strategies across diverse IoT architectures, contributing to the advancement of intelligent, data-driven energy management solutions in PV power generation.

Table 2: Comparison of IoT applications

IoT Application	Requirements	Techniques	Recommendations
Smart Home [114]	Data minimization, context awareness, reduced latency, energy-efficient (EE) data communication, security	Task offloading, data aggregation, social IoT, intelligent smart home solutions	Implement context-aware adaptations, minimize reaction time and latency, aggregate data to reduce transmission overhead, and utilize job offloading to enhance fault tolerance.
Agriculture [115]	IoT node reliability, sensor data handling, flexibility in deployment	Data compression, intelligent data collection, mobile energy transfer	Optimize sensor-based data compression and reduction, utilize mobile vehicles for energy transfer to field equipment, and employ

			intelligent mobile data collection to minimize transmission load.
Healthcare [116]	Low response time, node mobility, fault tolerance, security	Mobile energy transmission, social IoT integration, mechanical energy harvesting (EH)	Leverage mechanical energy harvesting and RF wireless charging for sustainable IoT power solutions, employ mobile energy transfer for charging mobile nodes, implement network softwarization to reduce latency and enhance security, and utilize social IoT for increased availability and fault tolerance.
Industrial IoT [117]	Low latency, fault tolerance, security, availability, mobility, adaptability, device heterogeneity, scalability	Cognitive radio IoT (CR-IoT), task offloading, mobile data collection, RF energy harvesting, mobile energy transfer, intelligent sleep/wake-up scheduling, network softwarization	Utilize RF wireless charging and intelligent mobile energy transfer to enhance energy efficiency, apply machine learning for optimized data collection and reduction, and implement real-time response optimization techniques to lower latency and improve system adaptability.

3 PV generations employs smart energy management systems

The global transition away from fossil fuels has led to an increasing dependence on renewable energy sources to meet rising energy demands in a sustainable and cost-effective manner [31, 32]. The integration of PV storage systems in grid-connected infrastructures has become essential, despite the inherent challenges associated with the intermittent nature of renewable energy generation [33]. To mitigate these challenges, the development and deployment of advanced energy forecasting models and optimized daily planning methodologies are imperative [34–35]. In response to these demands, an intelligent energy management system tailored for renewable energy integration has been developed to enhance demand-side management within smart grid environments. This system leverages advanced IoT-based frameworks to optimize the utilization of renewable energy resources [36–37]. Termed Intelligent Solar Energy Management Technology (ISEMS), this system comprises three key components:

Forecast-Based Intelligent Energy Management System: Utilizes predictive analytics to enhance energy availability forecasting, reducing uncertainty in solar power generation.

IoT-Enabled Energy Consumption Monitoring Framework: Employs real-time data acquisition techniques to analyze customer consumption patterns and optimize energy distribution.

Solar Energy Generation and Data Analytics Platform: Integrates PV generation data with machine learning algorithms to improve grid stability and energy efficiency. The primary objectives of ISEMS (intelligent smart energy management system) are to maximize energy efficiency, enhance the precision of energy demand forecasts, and facilitate the seamless integration of renewable energy sources into large-scale energy infrastructures. A detailed comparative analysis of ISEMS functionalities and benefits is outlined in Table 2.IoT was developed to enable seamless connectivity and communication among everyday devices, including computers, Smartphone, sensors, and actuators, via the Internet. This interconnectivity is facilitated through microchips, microcontrollers, transceivers, data acquisition modules, and standardized communication protocols [38–39]. IoT-integrated systems offer a more efficient and scalable alternative to traditional human inspection methods for monitoring and managing solar power systems, particularly in large-scale and remote installations [40].

The system presented in this study is designed to continuously monitor critical operational parameters, including voltage, current, temperature, and solar irradiance levels received by photovoltaic (PV) cells. These parameters are essential for optimizing energy conversion efficiency and diagnosing potential faults in solar power systems [41–42]. A NOdeMCU Wi-Fi transceiver is employed to facilitate wireless data transmission from an Arduino-based sensor module to an Internet-connected cloud platform. The acquired sensor data is then processed and visualized using ThingSpeak, an open-source IoT cloud platform for real-time data analytics [43]. A block diagram depicting the overall system architecture is illustrated in Fig. 2.

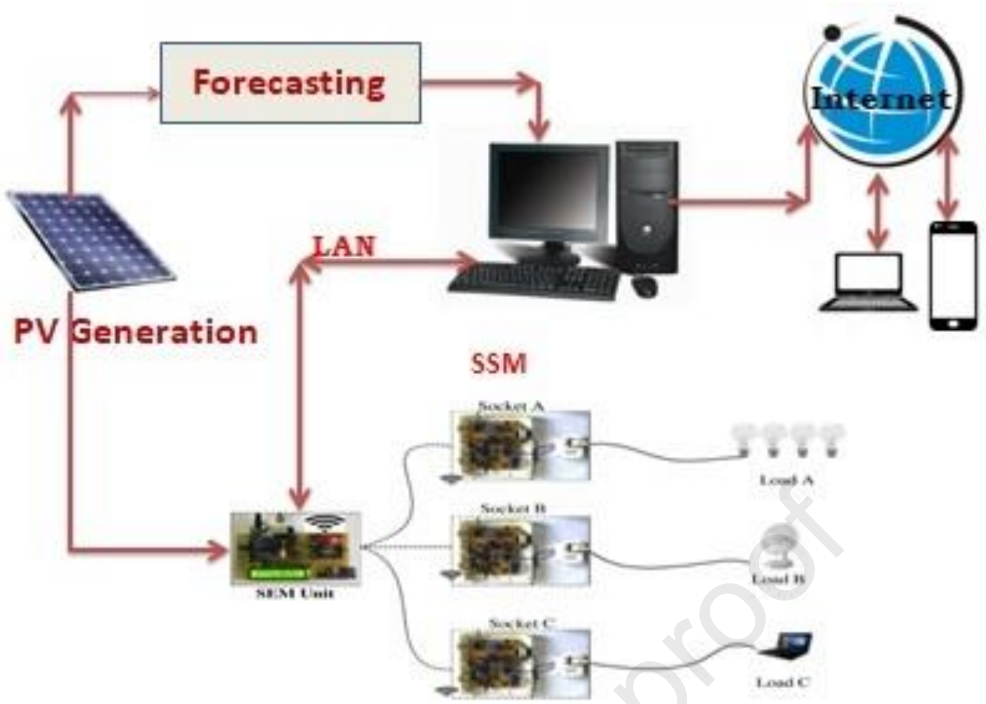


Fig.2. Smart energy management system [113]

The Arduino microcontroller is interfaced with a Wi-Fi module, enabling real-time sensor data transmission to the cloud. This data is then made accessible to users via a remote monitoring application, which continuously updates system parameters and provides insights into solar energy production and system performance [44–46]. Users must register an account or utilize a dedicated IP address to access the platform, which supports multiple channels for monitoring various network and system performance metrics, as outlined in Table 3.This cloud-based monitoring platform offers an intuitive online interface for visualizing real-time and historical solar power data, enhancing remote accessibility and operational efficiency [47–49]. A key advantage of this system is its ability to enable remote performance monitoring from any Internet-connected location, eliminating the need for on-site inspections. The system's gateway architecture, along with its data flow and component interactions, is schematically represented in Fig. 3.

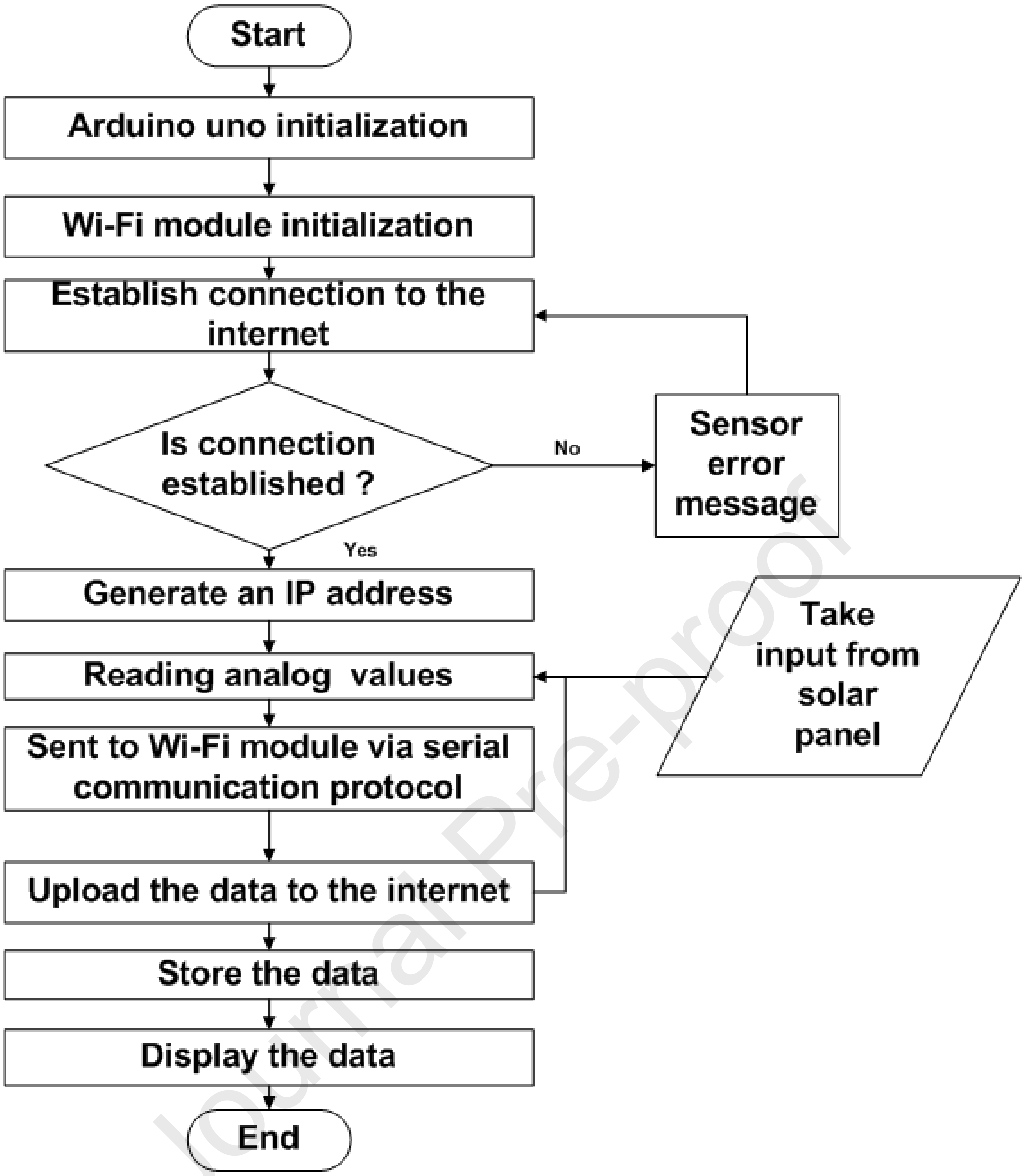


Fig.3. Diagram of PV monitoring system based on IoT [112]

Table 3: An illustration of an IoT-based PV monitoring system

Serial No.	Title of the Publication	Elements Employed	Technique for Energy Monitoring	Conclusion	Reference
1	Low-cost IoT-based energy monitoring system	Sensors, electrical energy measurement chip (SD3004, PZEM-004T)	ESP8266 wireless module with Arduino NodeMCU	Portable and simple installation on any device without affecting warranty	[50]
2	Smart Home for monitoring and control of	LDR sensor, PIR sensor, Wi-Fi, voltmeter, relay	Home energy management system	Supports smart grid applications	[51]

	electrical energy			with IoT and cloud computing	
3	IoT-based smart power metering	Relay, Wi-Fi module, transistor, current sensor	Studies on plug-level energy use and usage	Innovation in IoT to measure energy consumption	[52]
4	Monitoring and control of IoT-based electrical energy consumption	Raspberry Pi, AC/DC 50A, relay, Wi-Fi, current sensor, ACS DC8A	Power-use tracker for Raspberry Pi, data sent to Adafruit.io	Local data storage using Node.js and Raspberry Pi	[53]
5	IoT for intelligent energy management in buildings	Execution	Python-designed unique modules for data collection	IoT energy platform for data management	[54]
6	Decrease in power consumption utilizing IoT	YHDC SCT-013-000, CT sensor, burden resistor	IoT sensors linked to every device, data shared in the cloud	Energy conservation and carbon reduction with IoT sensors	[55]
7	IoT-based electrical energy monitoring system at MTU Melaka	Communication protocol	IoT device connects via Modbus protocol with digital energy meters	Optimizing energy use and reducing carbon footprints	[56]
8	IoT-based energy control and monitoring devices	Current sensor, LCD, RTC, relay, Wi-Fi	Automation of home appliances and solar energy tracking	Arduino controller transmits energy data to the cloud	[57]
9	Software model for an IoT-oriented and low-cost energy monitoring	Modern sensors	MQTT messaging protocol for decentralized IoT networks	Affordable energy monitoring platform	[58]
10	IoT-based digital kWh meter monitoring	LDR sensor, Wi-Fi module	IoT in smart grid applications	Wireless transmission of home appliance power usage	[59]

	system			data	
11	IoT-based intelligent energy tracking system	GSM, ADC, transformer sensor	IoT devices improving usability	Monitors lab occupancy to control electrical equipment	[60]
12	IoT-based smart energy meters	Light-dependent resistor	Remote device monitoring	IoT-enabled electric meters automatically count LED current consumption units	[61]
13	Energy modeling and monitoring via IoT devices	Communication protocol (ZigBee)	Software integrates data from BIM, IoT, GIS, meteorology	Reducing greenhouse gas emissions via ICT	[62]
14	Real-time energy analysis model for intelligent buildings	PZEM004T-100A module	Measures current, voltage, and power properties	99% accuracy in real-time energy usage data collection	[63]
15	Arduino-based IoT measurement system for residential energy	ACS712 Hall Effect current sensor, GSM SIM800L module	Energy consumption monitoring using Mechatronics principles	Adaptable system for accurate tracking	[64]
16	System monitoring system for buildings in Indonesia	ZMPT101B current sensor, voltage sensor, SCT 013-000 sensor	Transparent energy consumption reporting	Effective for obtaining construction permits by reducing energy/water usage	[65]
17	IoT-based smart energy meters	ESP8266, Wi-Fi, Max 232, GSM SIM900, signal state, relay	Selection of connection solutions based on multiple factors	Future expansion of IoT in utilities for reliable data collection	[66]
18	IoT-based domestic	Wi-Fi module, lithium-ion	Portable kWh meter	Addresses bulkiness and	[67]

	energy monitoring devices	battery, MSP430F6736 microcontroller		complexity of traditional meters	
19	IoT power monitoring for smart environments	Transformer, LoRa, sensor	SMACS control system for home energy monitoring	Ensures security and efficiency of appliances	[68]
20	Smart energy meters using IoT	Buzzer, relay, energy meter, UART communication, ESP 8266 12E	ESP 8266-based energy management	Resolves issues in existing metering systems	[69]
21	IoT-based smart energy monitoring	Power source, ESP8266, LCD, buzzer, current sensor	ESP8266-based energy tracking	Supports smart grid development	[70]
22	Real-time data collection to improve energy efficiency	Implementation	IoT-enabled EPE model	Enhances energy efficiency in the food industry	[71]
23	Monitoring of electrical power at industrial greenhouse	Implementation	Data sent to secure cloud service	Optimizes energy usage in commercial greenhouses	[72]
24	IoT-based Smart Home designs	Implementation	Ethernet-based monitoring for homes	Remote management of home appliances via voice commands	[73]
25	IoT-embedded Linux-based system on Raspberry Pi	Relative humidity, PV, solar radiation	Cloud-based monitoring without separate computers	Real-time monitoring of decentralized PV plants	[74]
26	Monitoring industrial processes using IoT	Wi-Fi module, ESP8266, MAX485 IC	Stable benchmark time sources	Real-time temperature and humidity monitoring for smart environments	[75]

27	IoT-embedded Linux-based systems on Raspberry Pi	Temperature, PV, relative humidity, sun radiation	Cloud-based decentralized PV plant monitoring	Ensures stability in power generation	[76]
28	IoT-based energy meter reading system	ESP8266, LCD, buzzer, relay, Wi-Fi, monostable multivibrator	Arduino IDE-based software	IoT-based system for fault detection, mode selection, and user alerts	[77]
29	IoT-based electrical energy monitoring system at MTU Melaka	Protocol for communication	Mod bus protocol for digital energy meter connectivity	Essential for efficient energy management	[78]
30	Smart-home Automation using IoT-based sensing	Air quality sensor, LDR, humidity sensor, LM35 sensor	Intelligent system monitoring	Enables automated smart homes	[79]
31	IoT-based real-time housing energy monitoring system	Optical sensor, NOdeMCU	Cost-effective modifications for energy meters	Popular and practical IoT-based application for energy tracking	[80]

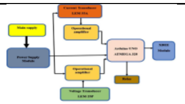
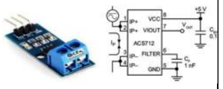
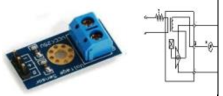
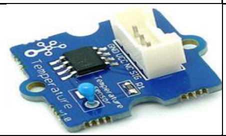
The analysis of IoT-based energy monitoring and management systems reveals a strong reliance on microcontrollers (ESP8266, Raspberry Pi, Arduino), current and voltage sensors, and wireless communication modules (Wi-Fi, GSM, LoRa) for real-time data collection. Cloud-based monitoring, smart home automation, and industrial energy optimization are key applications, enabling improved energy efficiency, cost reduction, and sustainability. These systems help track and control power usage, reducing carbon footprints while providing accurate, scalable solutions for future expansion. However, challenges such as high implementation costs, data security risks, and sensor reliability persist. Despite these limitations, IoT remains a promising technology for transforming energy management across residential, commercial, and industrial sectors.

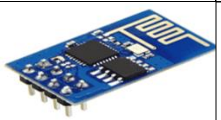
4 Developing a remote PV power generation monitoring system design

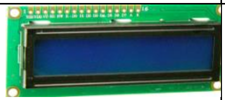
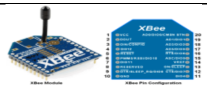
Designing an efficient solar monitoring system requires careful selection of components, precise specifications, and well-structured circuit diagrams to enable remote access to energy metrics and records [81-82]. This paper provides a detailed analysis of the essential equipment required for system development, including the selection and specifications of microcontrollers. Additionally, it examines the sensors used to measure key parameters such as voltage, current, and other critical factors necessary for accurate power calculations [83-84].

4.1 Component specification

In the component specification section, this paper thoroughly explores various components crucial for diverse work system designs. It provides detailed explanations of LCD standards, considerations for selecting and characteristics of Wi-Fi modules, and the integration of cloud-computing information. This section concludes with a comprehensive discussion of the components depicted in the circuit diagram of the IoT-based smart energy management system integrated with PV generation [85].

Component	Image	Description	Specifications	Applications
Smart Plug[86]		A device that allows you to control electrical devices remotely via an app or voice commands. It can also monitor power usage.	Voltage: 100-240V, Max Load: 10A/15A, Wi-Fi: 2.4GHz	Home automation, energy monitoring, remote device control
Current Sensor[87]		Measures the flow of electrical current in a circuit. Commonly used in power monitoring applications.	Range: 0-30A, Output: 0-5V, Accuracy: ±1%	Power management, fault detection, load monitoring
Voltage Sensor[88]		Measures the voltage across a component or in a circuit. Useful for monitoring and controlling voltage levels.	Range: 0-25V, Output: 0-5V, Accuracy: ±1%	Battery management, power supplies, electrical safety
Light Sensor[89]		Detects the presence and intensity of light. Used in automatic lighting, brightness control, and safety systems.	Sensitivity: 400-800nm, Output: Analog/Digital	Automatic lighting, ambient light detection, safety systems
Temperature Sensor[90]		Measures temperature in a variety of environments. Used in HVAC systems, weather	Range: -55°C to 125°C, Accuracy: ±0.5°C, Output:	Climate control, environmental

		monitoring, and industrial applications.	Digital (1-Wire)	monitoring, industrial process control
Arduino Uno[91]		A microcontroller board based on the ATmega328P. It is used for building digital devices and interactive objects that can sense and control physical devices.	Microcontroller: ATmega328P, Operating Voltage: 5V, Digital I/O Pins: 14 (6 PWM), Analog I/O Pins: 6	Prototyping, educational projects, interactive installations
NodeMCU [92]		An open-source IoT platform that uses the ESP8266 Wi-Fi module. It is used for prototyping and building IoT devices.	Wi-Fi: 802.11 b/g/n, Flash Memory: 4MB, GPIO Pins: 17	IoT applications, remote monitoring, smart home devices
Gateway [93]		Connects different networks, allowing data to flow from one network to another. Essential in IoT systems for managing communication between devices and the cloud.	Connectivity: Ethernet/Wi-Fi/Cellular, Protocols: MQTT, HTTP, Modbus	IoT networks, industrial automation, smart cities
Ethernet Module[94]		Ads wired internet connectivity to microcontroller projects. Commonly used for stable and secure data transmission.	Interface: SPI, Speed: 10/100Mbps, Voltage: 3.3V/5V	Networked sensors, secure data transmission, home automation systems
Wi-Fi Module[95]		Provides wireless internet connectivity to microcontroller projects. Widely used in IoT projects for remote control and monitoring.	Wi-Fi: 802.11 b/g/n, Voltage: 3.3V, Interface: UART/SPI/I2C	Wireless networking, IoT devices, remote control applications

PV Panel[96]		Converts sunlight into electrical energy. Used in solar power systems to generate renewable energy.	Power: 100W, Voltage: 18V, Efficiency: 15-20%	Solar power systems, off-grid applications, renewable energy projects
LCD Display[97]		A screen that displays information such as text and graphics. Used in various electronic projects to provide visual feedback.	Size: 16x2 characters, Interface: I2C/SPI, Voltage: 5V	User interfaces, data display, educational projects
Battery[98]		Stores electrical energy for use in powering devices and systems. Available in various types and capacities.	Type: Li-ion, Capacity: 2000mAh, Voltage: 3.7V	Portable electronics, backup power supplies, renewable energy storage
XBee[99]		RF modules for wireless communication, operates in various frequency bands (e.g., 2.4 GHz), provides serial communication.	Wireless sensor networks, remote monitoring	XBee
Wi-Fi[100]		Wireless network standard (e.g., IEEE 802.11), provides internet connectivity without physical wires.	Mobile devices, smart home appliances	Wi-Fi

The table presents a comprehensive overview of key components used in IoT-based energy monitoring and automation systems. It includes sensors for measuring voltage, current, temperature, and light, which are essential for accurate power and environmental monitoring. Microcontrollers like Arduino Uno and NOdeMCU serve as the core processing units, enabling seamless integration of sensors and communication modules. Connectivity options such as Wi-Fi modules, Ethernet modules, and gateways facilitate data transmission and remote access, making real-time monitoring possible. The inclusion of smart plugs and LCD displays enhances usability, allowing users to interact with and control their devices efficiently. Power sources such as PV panels and batteries ensure sustainability and energy storage, particularly in solar-powered applications. Additionally, communication modules like XBee and Wi-Fi enable wireless data exchange in smart home and industrial environments. Overall, these components collectively contribute to the development of intelligent, efficient, and remotely accessible energy monitoring systems.

5 Communication technologies of IoT

This refers to a somewhat ambiguous selection of component choices for contemporary applications, primarily focusing on IoT-connected network systems and devices. Illustrate the principal IoT data transmission technologies.

Technology	Frequency Range	Data Rate	Range	Application	Power Consumption	Key Features	Reference
IEEE 802.15.4	868/915 MHz, 2.4 GHz	20-250 kbps	10-100 meters	Low-rate WPAN (e.g., ZigBee)	Low	Low power, short range, mesh networking	101
Zigbee (based on 802.15.4)	2.4 GHz	20-250 kbps	10-100 meters	Home automation, industrial control	Very low	Mesh networking, low data rate, secure	102
Long-Term Evolution (LTE)	700 MHz - 2.6 GHz	Up to 1 Gbps	Several kilometers	Mobile broadband	Medium to high	High data rate, wide area coverage, supports mobility	103
Near-Field Communication (NFC)	13.56 MHz	106-424 kbps	~10 cm	Contactless payments, access control	Very low	Very short range, secure, peer-to-peer communication	104
Ultra-Wide Band (UWB)	3.1-10.6 GHz	110 kbps - 1+ Gbps	<10 meters	High precision location, short-	Low	High precision, high data rate, low	105

				range comes		interference	
Machine to Machine (M2M)	Varies (often LTE, LPWAN)	Varies (kbps to Mbps)	Varies (depends on tech)	IoT applications	Varies (often low)	Supports a wide range of devices, scalable	106
IPv6 Low-Power Wireless PAN (6LoWPAN)	868/915 MHz, 2.4 GHz	20-250 kbps	10-100 meters	IoT, smart metering	Very low	IPv6 support for low-power devices, mesh networking	107
5G	6 GHz, 24-100 GHz	Up to 10 Gbps	Several kilometers	Enhanced mobile broadband, IoT, V2X	Medium to high	Extremely high data rates, low latency, massive connectivity	108
Wireless HART	2.4 GHz	250 kbps	10-100 meters	Industrial automation	Low	High reliability, secure, mesh networking	109
Bluetooth	2.4 GHz	1-3 Mbps	~100 meters	Personal Area Networks, audio streaming	Medium	Universal compatibility, moderate range, medium data rate	110
Bluetooth Low Energy (BLE)	2.4 GHz	125 kbps - 2 Mbps	~100 meters	IoT, health devices, wearable	Very low	Very low power consumption, short bursts of data transfer	111

Wireless communication technologies vary in frequency range, data rate, range, power consumption, and application suitability. Low-power, short-range networks such as IEEE 802.15.4, Zigbee, 6LoWPAN, and Wireless HART operate in the 2.4 GHz band and support mesh networking, making them ideal for IoT, industrial automation, and smart metering. In contrast, high-data-rate, wide-area networks like LTE and 5G provide extensive coverage, with LTE reaching up to 1 Gbps and 5G exceeding 10 Gbps, enabling mobile broadband, IoT, and V2X communications. Specialized technologies such as UWB (3.1-10.6 GHz) and NFC (13.56 MHz) cater to high-precision location tracking and secure contactless transactions, respectively. Bluetooth and BLE, both operating at 2.4 GHz, facilitate medium-range personal and industrial networks, with BLE optimized for low-power applications. Machine-to-Machine (M2M) communication, often leveraging LTE and LPWAN, enables scalable IoT deployments across diverse industries. The choice of technology depends on specific requirements such as range, data rate, network topology, and energy efficiency, with each solution tailored to optimize connectivity and performance for its intended application.

Comparison of Energy Management Techniques

Various energy optimization techniques are used in IoT-based smart PV energy management. The following table compares rule-based control, machine learning, AI-based predictive optimization, and edge computing across key performance metrics.

Technique	Efficiency Improvement (%)	Energy Savings (%)	Fault Detection Accuracy (%)	Response Time (ms)	Cost Effectiveness
Rule-Based Control	5-10%	5-8%	50-70%	500-1000 ms	High (low investment)
Machine Learning (ML)	15-25%	10-15%	70-85%	200-500 ms	Medium
AI-Based Optimization	20-35%	15-25%	85-95%	100-300 ms	Medium-High
Edge Computing + AI	30-40%	20-30%	95-99%	50-200 ms	High (higher investment)

Rule-Based Control Systems

Traditional PV energy management relies on predefined rule-based algorithms, which adjust energy flow based on set thresholds (e.g., turning on storage when excess energy is detected). These methods are simple and cost-effective but lack adaptability and real-time optimization, leading to lower energy savings (5-8%) and slow response times (500-1000 ms).

Machine Learning-Based Optimization

ML (machine learning) models improve decision-making by analyzing historical energy usage patterns, weather conditions, and load demand. This technique increases efficiency by 15-25% and provides better adaptability compared to rule-based methods. However, MLmodels require continuous training and computational resources, making them moderately expensive to implement.

AI-Based Predictive Optimization

AI-driven energy forecasting and predictive load balancing allow dynamic adjustments based on real-time sensor data, demand fluctuations, and grid conditions. These systems enhance fault detection accuracy up to 95% and increase energy savings by 15-25%. However, cloud-based AI processing can introduce delays, especially in remote installations.

Edge Computing with AI

Integrating AI with edge computing significantly reduces latency and improves response times (50-200 ms) by processing data locally instead of relying on cloud-based computation. This approach achieves the highest efficiency improvements (30-40%) and energy savings (20-30%) by enabling real-time optimization, fault detection, and automated decision-making. The main challenge is higher initial investment costs, but long-term savings and improved performance justify the expense.

Key Findings and Recommendations

For Small-Scale PV Systems: Rule-based or ML-based systems offer a cost-effective solution with moderate efficiency gains.

For Industrial and Large-Scale Solar Plants: AI-driven optimization provides higher energy savings and faster decision-making, improving overall grid stability.

For Critical Applications (e.g., Smart Microgrids): Edge computing with AI ensures the best real-time performance and highest fault detection accuracy, making it the most reliable choice.

Future Research Direction: Hybrid approaches combining ML, AI, and edge computing can further optimize energy management, making IoT-based PV systems more intelligent and autonomous.

6. Conclusion

This study analyzed the strategies, methodologies, and system architectures employed in hybrid renewable energy systems, encompassing both grid-connected and stand-alone configurations, with a focus on optimizing energy management. Particular emphasis was placed on energy management frameworks in PV power generation. The findings indicate that IoT is integral to the proposed Integrated Smart Energy Management System (ISEMS), as it facilitates real-time data acquisition and bidirectional control of connected devices, thereby enhancing power management efficiency for both end users and energy service providers. The study highlights IoT as a pivotal technology for intelligent power monitoring and control, enabling precise, reliable, and effective energy tracking. The ISEMS provides users with real-time insights into power consumption, allowing them to identify and mitigate unnecessary energy usage, ultimately leading to improved efficiency and reduced electricity costs. Furthermore, the proposed system enables continuous online monitoring of electrical parameters via a communication gateway, actively minimizing standby power losses and optimizing outlet power consumption. By offering preemptive power consumption insights before the monthly billing cycle, the smart energy monitoring system enhances consumer awareness and control over electricity usage. The proposed system can establish a closed-loop power communication framework, contributing to the implementation of a smart grid by leveraging cloud computing technologies for advanced energy management.

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- In the energy sector, there is a need for an integrated co-operative operational mechanism taking into account of power supply and demand entity to reduce the mismatch.
- The power management operational task seeks for the development of inexpensive and efficient Smart Energy Management System (SEMS). Further, deployment of power negotiating algorithms with reliable communication capability is essential to reduce the overall power consumption and hence, minimize the electricity cost.
- A comprehensive initiative in smart grid is essential, which includes energy management framework associated with an IoT environment that monitors and visualizes power consumption at the consumer premises.
- Optimization techniques are to be evaluated to find the cost effective and computationally efficient approach for the given demand side consumer constraints.
- Accurate prediction of power generation or power availability is required for Proper scheduling mechanism.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: